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Research Article

Coherent and Incoherent Scattering Cross Sections of Some Lead and Sodium Compounds at Angles below 10° for ^{241}Am Gamma Rays

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We report the total (coherent + incoherent) scattering cross sections of some lead and sodium compounds measured at angles less than 10° for ^{241}Am (59.54 keV) gamma rays. The experimental cross sections so obtained are compared with the data interpolated from theoretical compilations based on nonrelativistic Hartree-Fock (NRHF) model for the samples of interest. In the low momentum transfer region studied, it is observed that the nonrelativistic theoretical total scattering cross sections computed using HF form factor and scattering function tabulated by NRHF are quite adequate in explaining the measured total scattering cross sections.

1. Introduction

Scattering of gamma rays at small scattering angles by materials involves low momentum transfer to the struck electron. In the incident energy region above 50 keV up to say 1000 keV, for scattering angles less than 10°, it is difficult to separate out the coherent scattering from the main peak particularly due to the severe limitations imposed as a result of the finite resolution of the detector. Hence, several methods have been reported in the literature to remedy this problem. It may be observed that the shadow cone method, although widely used for this purpose, suffers from a number of drawbacks. The limitations of the other methods used at small angles have also been pointed out in the literature [1–4]. So there is a need for measuring the scattering cross sections at forward angles using a different experimental method involving minimum corrections.

In the present work, such a method [5], for measuring the scattering cross sections of gamma rays at small angles, which uses a simple geometrical setup similar to that of the experimental setup employed for the measurement of total attenuation cross sections was described earlier [5] by one of the authors. Recently, this method was used to determine the total scattering cross sections of some alloys by us [6, 7]. This method is simple and involves only the measurement of the scattered intensity superposed as a small addition to the direct transmitted beam. It makes use of a NaI(Tl) detector, to determine experimentally the total (coherent + incoherent) scattering cross sections of the samples. In the present work, we have reported the measured total scattering cross sections of the lanthanum compounds measured at angles 4°–10° at 59.54 keV by this method.

2. Experimental Details

2.1. Method. While in the total attenuation cross section measurements extreme care is taken to prevent the scattered photons from reaching the detector by selecting a very small angle of acceptance, in the present study, the scattered photons at low angles are allowed to reach the detector by increasing the angle of acceptance of the detector. The spectra, therefore, contain both the transmitted photons and the photons scattered within the cone covered by the detector with the vertex at the scatterer. In order to obtain the contribution of the scattered photons, the usual attenuation

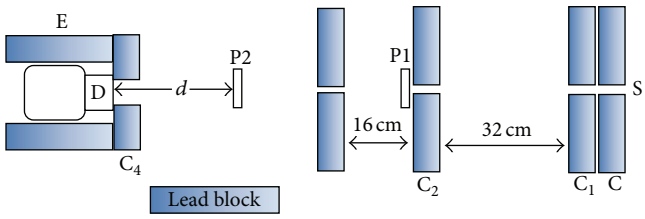

Figure 1: The experimental setup (not to scale). S is the source, D is the NaI(Tl) detector, C, C_1, C_2, C_3, and C_4 are lead collimators, E is the lead shielding around the detector, and P1 and P2 are the scatterer positions.

coefficient measurement setup is slightly modified and the schematic diagram of the experimental setup used in the present study is shown in Figure 1.

The source S, of strength 200 mCi of ^{241}Am in the form of a steel-welded capsule, was located in a lead collimator C. The detector D, ($2'' \times 2''$) NaI(Tl) crystal supplied by Electronic Corporation of India Limited (ECIL), Hyderabad, India, was mounted in a lead housing. The profile of the gamma beam was shaped by using the collimators C_1, C_2, and C_3. Each of the collimators C_1, C_2, C_3, and C_4 was about 7 cm in thickness. The collimators C_2 and C_3 were kept separated by a distance of 12 cm. The detector was placed at a distance of 40 cm from C_3. The collimator C_4 diameter is slightly larger than the diameter of the NaI(T1) crystal can, symmetrically about its collimating hole of diameter 4.18 cm. The NaI(T1) crystal is fitted into this step groove and thereby the centroid of the crystal with respect to the C_4 collimator hole is fixed automatically.

The ^{241}Am was procured on a loan basis from the Department of Physics, Mangalore University. Lead and sodium compounds of uniform thickness were used as scatterers placing them at position P1 or P2 alternately in the path of the beam. Their maximum thickness (mass per unit area) was chosen to be about one mean free path in order to minimize the multiple scattering and to achieve an absorption of 30–80% of the original intensity [8]. The detection system used in the present studies consisted of a scintillation head, high voltage unit, low voltage supply, linear amplifier, and a multichannel analyzer. The scintillation head of the type SH 644, supplied by Electronics Corporation of India Limited (ECIL), Hyderabad, India, which is built into a complete unit comprising of a scintillator, photomultiplier, and preamplifier was used. The scintillator used was a thallium activated ($2'' \times 2''$) sodium iodide [NaI(Tl)] crystal. The resolution of the detection system used was about 8% for the gamma rays of interest. The detector signal was further amplified by a linear amplifier and the spectrum was analyzed in a personal computer based 8 K multichannel analyzer. The entire experiment was carried out in an air-conditioned room wherein the mains' voltage was stabilized.

3. Results and Discussion

In order to define the angle of scattering, the gamma beam has to be made as narrow as possible so that the area of the scatterer exposed to the beam can be treated as a point scatterer for all practical purposes. The modified setup permits one to have a highly collimated sharp beam of photons as the collimator C with a very narrow collimating hole was used. In addition, the separation distances between C_2, C_3, and D were chosen such that the gamma beam emerging out of C_3 was practically of the same diameter up to the detector. When the scatterer is at position P1, the angle of acceptance is about 0.1°, which is entirely determined by the collimator C_3. This gives a scattering contribution less than 0.01 b/mole, which is negligible. Hence, the intensity I_1 recorded by the detector is considered to be free from the scattered photons and is given by the familiar attenuation relation:

$$I_1 = I_o \exp(-\mu t) \quad \text{or } \mu t = \ln\left(\frac{I_o}{I_1}\right), \tag{1}$$

where I_0 is the direct beam intensity without placing the scatterer at either position, μ is the attenuation coefficient in cm^2/g, and t is the mass per unit area of the scatterer. On the other hand, when the scatterer is at position P2, the detector detects the photons scattered inside the cone bounded by the detector with vertex at P2 in addition to the transmitted photons. Thus, for the same scatterer of mass per unit area t, the attenuation coefficient will decrease by a small amount $\Delta\mu$ so that

$$(\mu - \Delta\mu)\, t = \ln\left(\frac{I_o}{I_2}\right), \tag{2}$$

where I_2 is the intensity recorded by the detector when the scatterer is at position P2.

From (1) and (2), one can deduce an expression for the scattered contribution:

$$\Delta\mu = \frac{\ln(I_2/I_l)}{t}\ \text{cm}^2/\text{g}. \tag{3}$$

Then, by expressing $\Delta\mu$ in cm^2/mole and writing it as $\Delta\sigma_{sca}$ we have

$$\Delta\sigma_{sca} = \left(\frac{A}{Nt}\right)\ln\left(\frac{I_2}{I_1}\right)\ \text{barn/mole}, \tag{4}$$

where A is the molecular weight, t is the mass per unit area of the scatterer, and N is the Avogadro number. Equation (4) was used to find the integrated scattering cross sections between 0° and the corresponding angle, θ, subtended by the detector with respect to the scatterer at position P2. The angle of scattering can be varied by varying the angle of acceptance of the detector at the scatterer position P2.

In this manner, the total (coherent + incoherent) scattering cross sections were obtained in the angular range (0–4°), (0–6°), (0–8°), and (0–10°). These values are shown in Table 1.

The experimental errors were to the extent of 3%–5%. The possible source of errors was mainly due to counting statistics, nonuniformity of scatterer material, sample impurity, and photon dose buildup inside the scatterer. The detailed error calculations were published elsewhere [9].

The theoretical cross sections were calculated by interpolating the data of Hubbell et al. [10] for the constituent

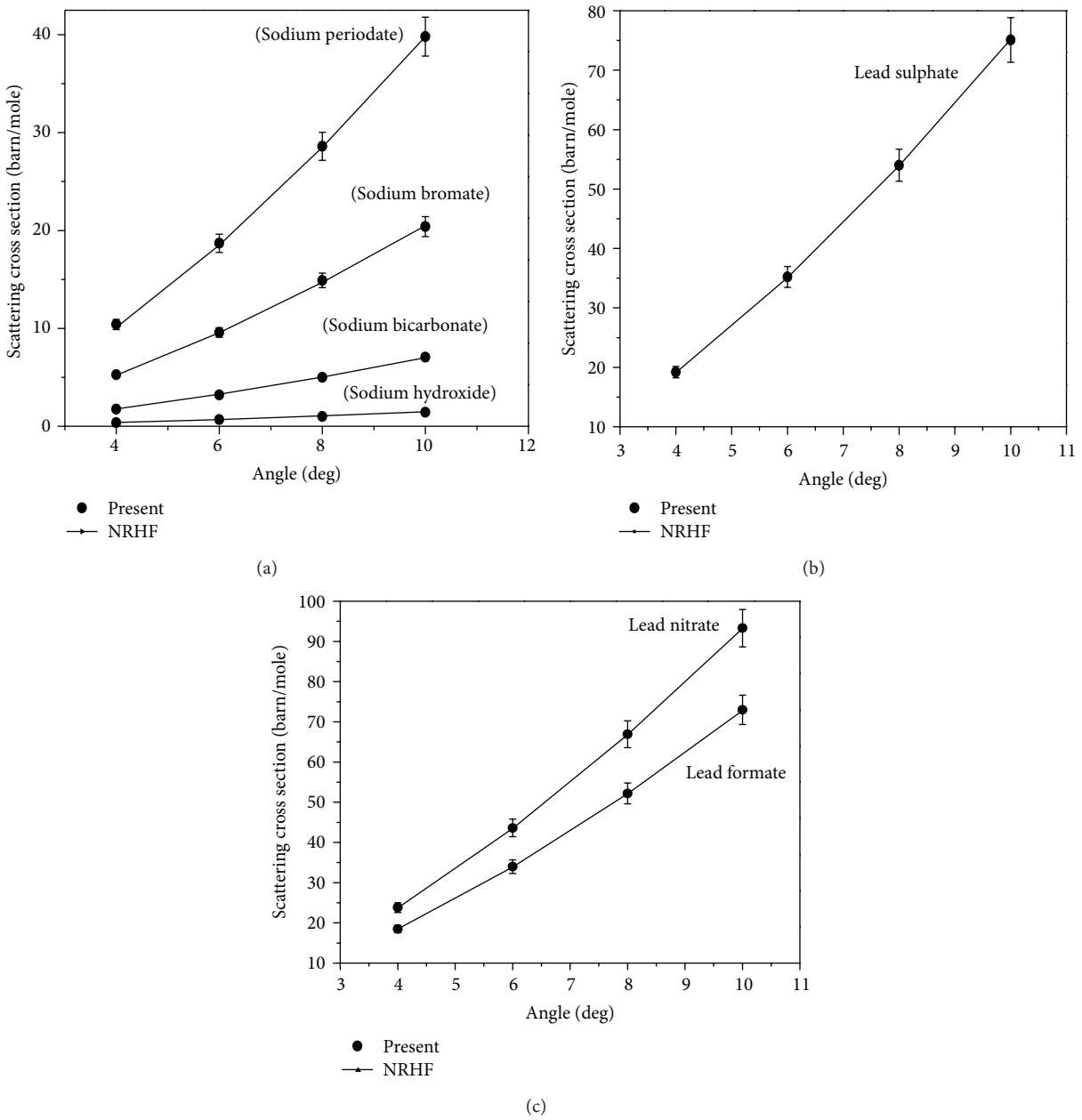

Figure 2: Plot of total angle integrated scattering cross section in barn/mole versus scattering angle in degree.

elements in the momentum transfer grid corresponding to 0.01° interval for the experimental scattering angles and then the integrated scattering cross sections of the lead and sodium compounds were derived with the aid of mixture rule. Further, the theoretical scattering cross sections were calculated by a numerical integration in intervals of 0.01° using form factor and incoherent scattering functions along with the Thomson scattering cross section and Klein-Nishina cross sections in the integrand, respectively (see Hubbell et al. [10] for the integral), to calculate the angle integrated coherent and incoherent scattering cross sections in the range (0–4°), (0–6°), (0–8°), and (0–10°), respectively. The sum of these two cross sections was taken to be the theoretical total scattering cross section for the compound. These values are also shown in Table 1. The values in Table 1 were plotted as a function of scattering angle. The resulting plot is as shown in Figure 2. The measured total scattering cross sections of the lead and sodium compounds shown were found to be in agreement with the nonrelativistic theoretical total scattering cross sections tabulated by Hubbell et al., [10] within the range of experimental errors.

4. Conclusions

Thus, it has been possible in the present work to measure the angle integrated total (coherent + incoherent) scattering cross

Table 1: Total (coherent + incoherent) scattering cross section of 59.54 keV gamma rays for some lead and sodium compounds (barn/mole). (Experimental errors are to the extent of 3% to 5%).

Compounds	d in cm	Angle θ in deg	Total scattering cross section $\Delta\sigma_{sca}$ (coh + incoh) (in barn/mole)	
			Present	NRHF
Sodium hydroxide (NaOH)	29.88	4	0.37 ± 0.01	0.38
	19.88	6	0.67 ± 0.02	0.69
	14.87	8	1.01 ± 0.05	1.06
	11.85	10	1.43 ± 0.05	1.48
Sodium bicarbonate ($NaHCO_3$)	29.88	4	1.74 ± 0.04	1.78
	19.88	6	3.21 ± 0.06	3.27
	14.87	8	5.00 ± 0.02	5.02
	11.85	10	7.05 ± 0.04	7.01
Sodium bromate ($NaBrO_3$)	29.88	4	5.27 ± 0.05	5.22
	19.88	6	9.58 ± 0.03	9.55
	14.87	8	14.90 ± 0.20	14.70
	11.85	10	20.40 ± 0.10	20.50
Sodium periodate ($NaIO_4$)	29.88	4	10.40 ± 0.31	10.10
	19.88	6	18.70 ± 0.20	18.50
	14.87	8	28.60 ± 0.10	28.50
	11.85	10	39.80 ± 0.00	39.80
Lead format $Pb(CHO_2)_2$	29.88	4	18.48 ± 0.02	18.50
	19.88	6	34.00 ± 0.10	33.90
	14.87	8	52.20 ± 0.10	52.10
	11.85	10	73.00 ± 0.20	72.80
Lead sulphate $PbSO_4$	29.88	4	19.20 ± 0.10	19.10
	19.88	6	35.20 ± 0.10	35.10
	14.87	8	54.00 ± 0.10	53.90
	11.85	10	75.10 ± 0.10	75.20
Lead nitrate $Pb(NO_3)_2$	29.88	4	23.80 ± 0.10	23.70
	19.88	6	43.60 ± 0.10	43.50
	14.87	8	66.90 ± 0.10	66.80
	11.85	10	93.30 ± 0.10	93.20

sections at very low angles by using a NaI(Tl) detector by a simple method. To the knowledge of the authors, these results are first of their kind at this energy.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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